

A. Küchler / T. Leibfried / B. Breitenbauch /
J.J. Alff / V. Der Houhanessian / W.S. Zaengl

Transformer Insulation Diagnosis by Polarization and Depolarization Current Analysis

Abstract: Insulation diagnosis is of increasing importance for evaluation of transformers and other HV equipment. Dielectric diagnosis with polarization and depolarization currents (PDC) uses the dielectric system response in time domain. A single measurement allows to distinguish the influences of material properties and geometrical structures, e.g. in an oil-board barrier system. Measurements on transformer insulation models have shown that oil conductivities, board conductivities and water contents in the barriers can be quantified. PDC measurements were applied to the evaluation of water content in transformer insulation barriers in different applications. Results are compared with other diagnostic methods. Examples are measurements on new transformers in the factory which were compared with Karl-Fischer-Titration and dew-point measurements. Measurements on an aged transformer before and after drying and oil exchanging procedures are compared with RVM and power factor measurements at 0.1 Hz. PDC evaluation seems to be a reliable tool for determination of water content in the barriers and of oil conductivities. Further options are related to ageing diagnosis, measurement of grounded objects and to the evaluation of mounted bushings.

1. INTRODUCTION

Reliability of power transformers is most important for a safe and economic operation of distribution networks. Unfortunately many transformers are operated in an unknown state of ageing. Here the accumulation of water is one of the most severe problems. Water drastically reduces the

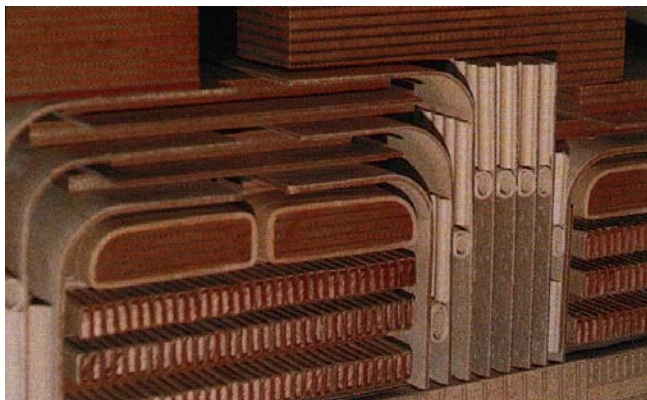
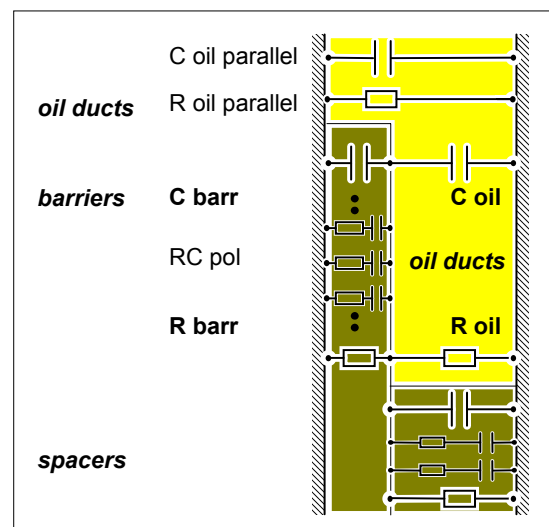


Fig. 1: Transformer insulation system model (Weidmann TBS AG) and equivalent circuit description.



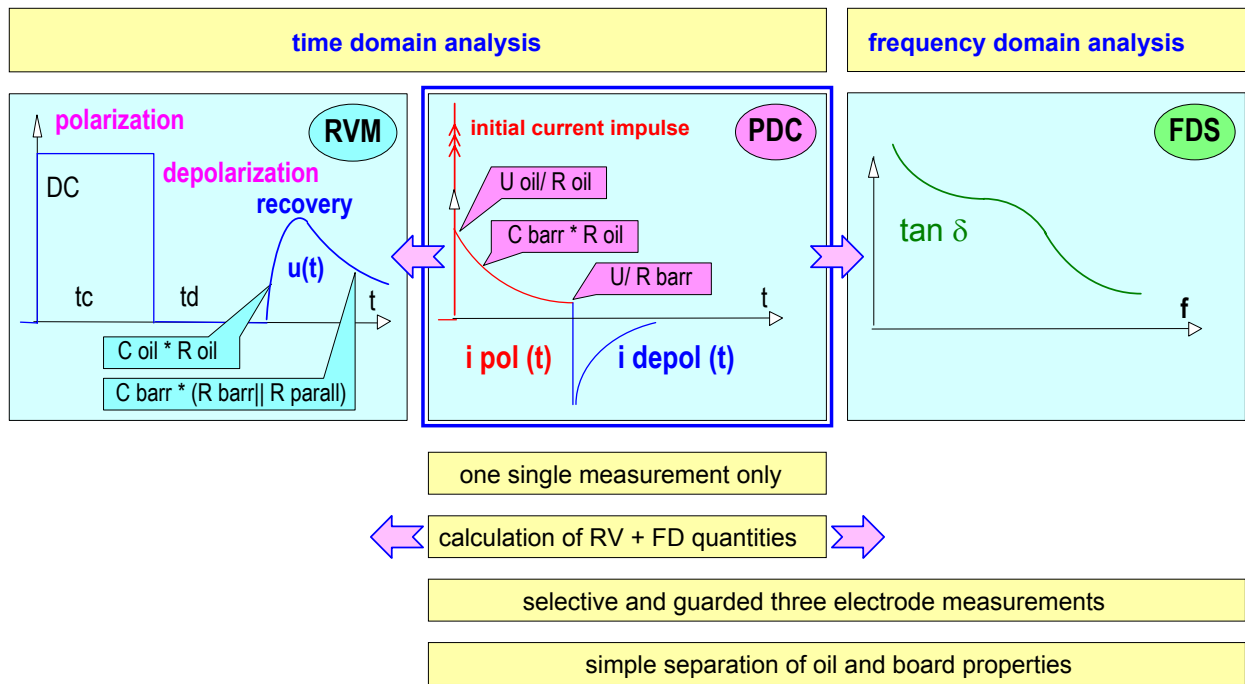


Fig. 2: Dielectric diagnosis in time and frequency domain by recovery voltage measurements RVM, polarization and depolarization currents PDC and frequency domain spectroscopy FDS.

electric strength of oil. Water also increases the rate of depolymerisation of cellulose molecules and reduces the dielectric strength of solid insulation.

Analysis of oil samples gives information about the oil alone. Solid insulation components are very hygroscopic, they can be humid, even if the oil is dry. Therefore solid insulation could only be supervised unequivocally by opening of the transformer and taking samples from the insulation. Obviously, this is not possible in most cases. Up to now there is no commonly accepted method for a non-destructive evaluation of solid insulation. Therefore, there is a high requirement to use dielectric diagnosis methods, i.e. to relate test voltages and currents to insulation properties.

2. DIELECTRIC DIAGNOSIS

Transformer insulation systems consist of barriers subdividing oil ducts in order to increase dielectric strength [1]. Application of specific test voltages to such a system results in dielectric responses being very much influenced by the geometry of the insulation [8]. The interpretation of dielectric system responses has to take into account complex equivalent circuits for the different insulating parts, fig. 1. There are three different approaches for dielectric diagnosis [15], fig. 2:

(1) Frequency domain spectroscopy FDS allows to distinguish different materials at different frequency ranges [6]. Every frequency, which has to be regarded, requires an own measurement at stationary conditions.

(2) Polarization and depolarization currents PDC contain information about the oil conductivity within the first seconds after a DC voltage step application and about the barrier conductivity in a long term range. PDC measurements can be used to distinguish different materials at different times [4, 5, 7 – 12, 14, 16]. They are step response measurements and contain all the information about the system in one single measurement. From PDC results, also frequency domain quantities for FDS can be derived at low field strengths with linear material behaviour. The calculated frequency domain information is in agreement with directly measured loss factors [11, 12, 14, 16].

(3) Another time domain method makes use of recovery voltages which are used for a special recovery voltage method RVM [2, 3]. Recovery voltages can be measured directly or can also be calculated from PDC system responses [7]. For the results of RVM method, up to now, no evaluation procedure is published how to distinguish the influences of insulation system geometry, barrier properties and transformer oil properties.

3. INSULATION MODELS

Insulation models were made of two Transformerboard-discs (Weidmann T IV/ 1 mm) with different water contents, separated by an oil duct with different spacings between 0 and 9.6 mm, fig. 3. Different dielectric measurements were made in order to distinguish the influences of water content in the barriers and insulation system geometry [8, 10]:

This goal could be achieved by resistance and PDC measurements, but not by RVM and power frequency $C/\tan \delta$ measurements [8]. **End values of polarization currents** are determined by the series resistance of oil gaps and barriers which is dominated by the barrier resistance being directly related to the water content, fig. 3 (top and bottom).

Initial values of the polarization current are related to the oil conductivity.

The **transient current variation** is determined by geometry and oil properties, fig. 3 (left and right). I.e. the barrier capacitances are charged via oil gap resistances (interfacial polarization).

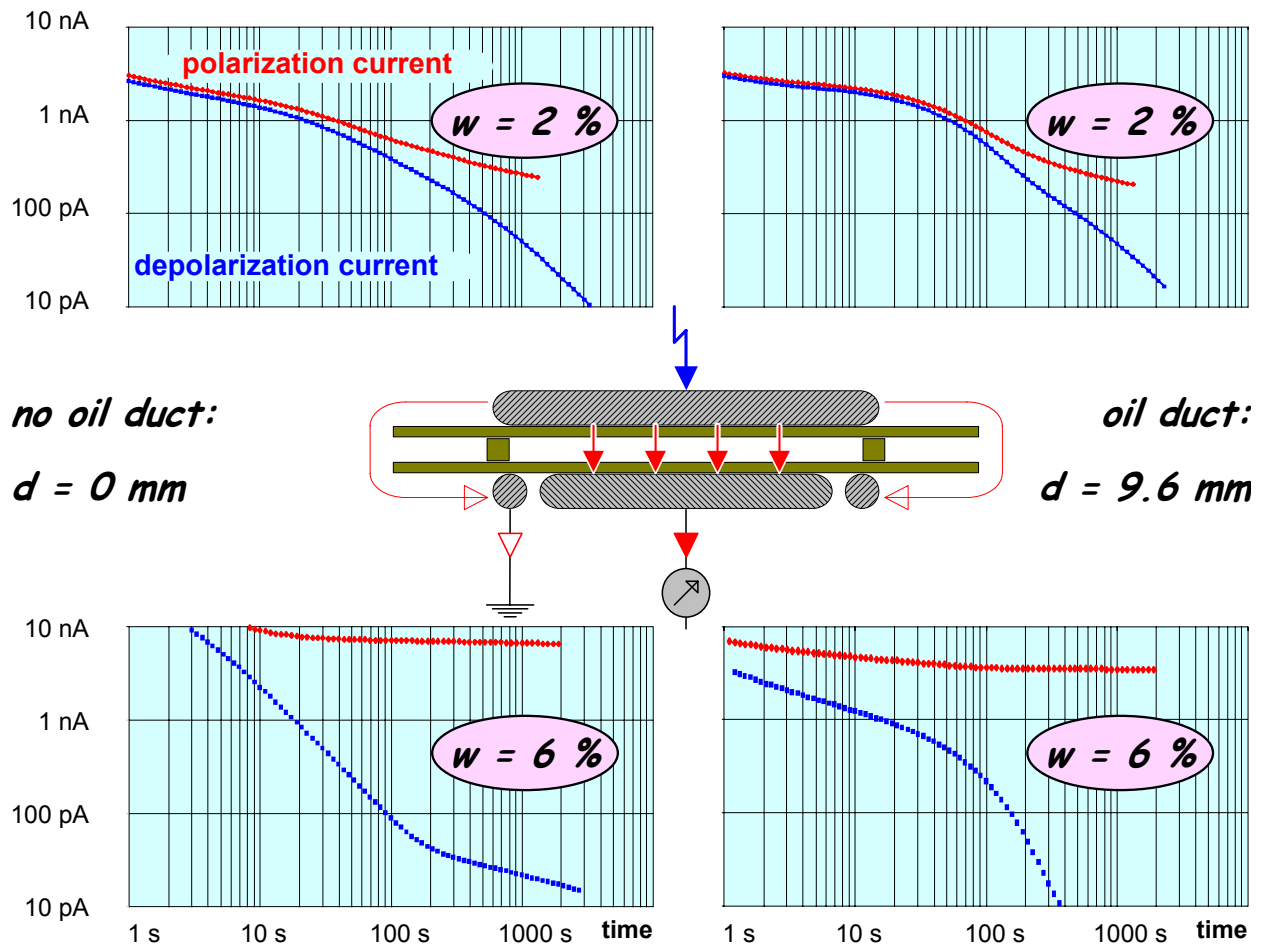


Fig. 3: Influence of water content and barrier geometry for oil-barrier insulation models.

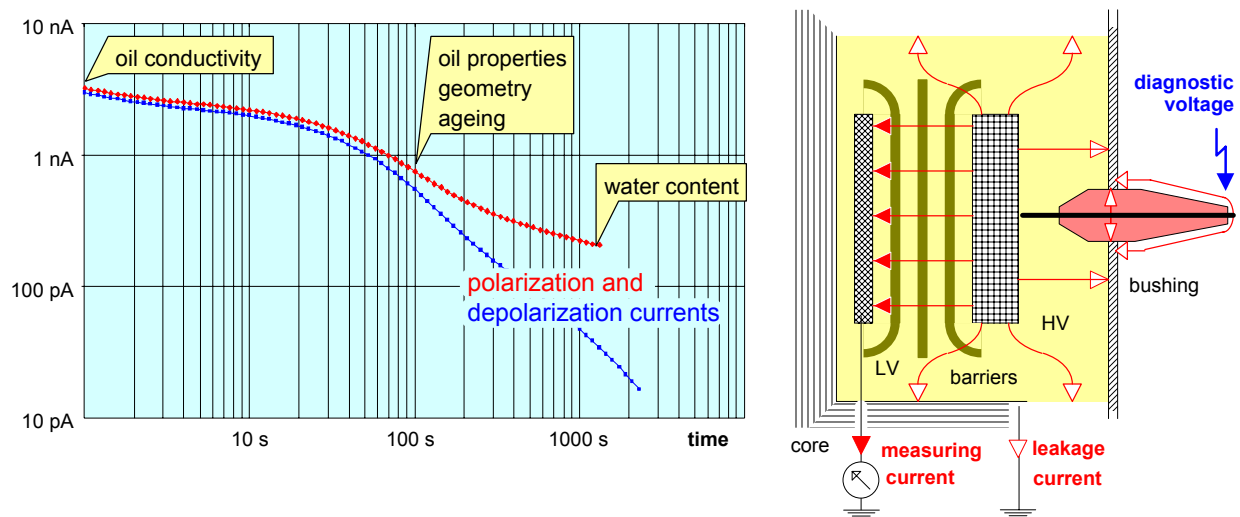


Fig. 4: Main influences on PDC curves in transformer oil-barrier systems.

4. TRANSFORMER DIAGNOSIS

PDC measurements on transformers can be performed by applying the diagnostic voltage to the HV terminations, fig. 4 (right). The measured current originates exclusively in a well defined geometry between HV and LV windings and it is taken from the LV terminations. All leakage currents on the bushing surfaces or between windings and core or tank, are directly conducted to ground and do not superpose to the measuring current, fig. 3 (left). Therefore PDC measurements allow some kind of selectivity which is not possible for recovery voltage measurements.

Similar to insulation models, PDC measurements on transformers also are determined by oil conductivity during the first seconds. During the transition process signals are strongly influenced by geometry, oil conductivity and ageing products. In a long term range the water content in the barriers plays a dominant role, fig. 4 (left).

Based on some information about transformer geometry, water content in the barriers can be calculated. This can be done by generation of equivalent circuits, simulation of PDC curves, comparison with measured curves and iterative curve fitting by variation of barrier properties which have a known relation to water content [7].

5. EXPERIENCES

Comparison of PDC analysis with other methods

In Siemens transformer factory in Nuremberg comparisons between PDC analysis, Karl-Fischer-Titration and dew-point measurement have been carried out on numerous transformers with different ratings and designs. PDC results show a good match with the other methods, fig. 5 [16].

Oil exchange and drying of a 300 MVA Power Transformer

After 23 years of operation a 300 MVA power transformer was found to have sludge in the oil. It was decided to exchange the oil and to perform diagnostic measurements as PDC, RVM and $\tan \delta$ at 0.1 Hz, both before and after the oil exchange.

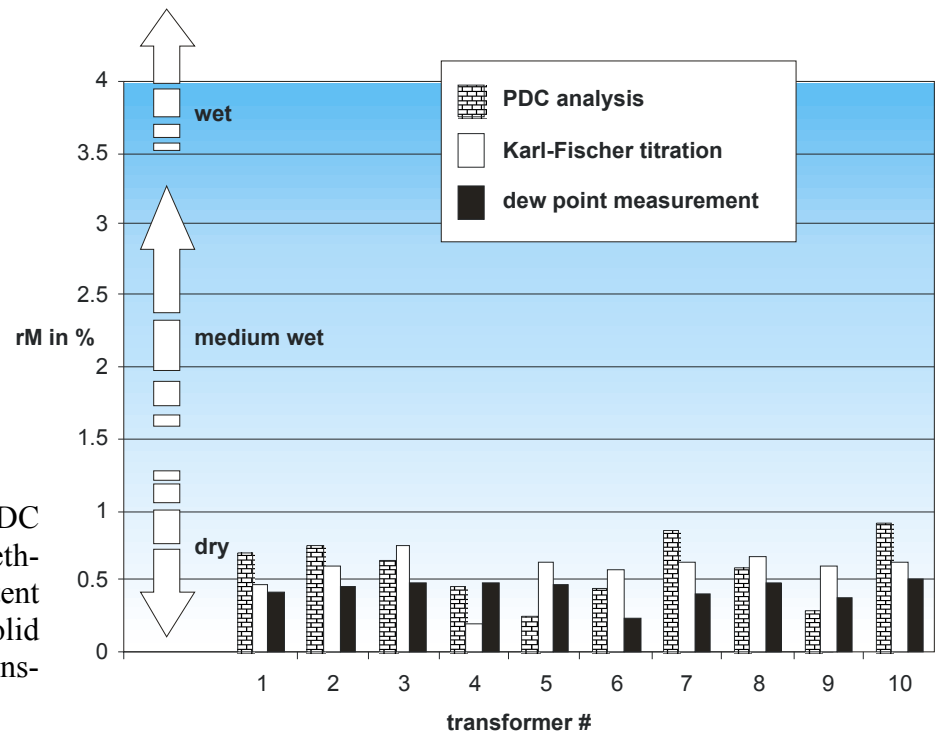


Fig. 5: Comparison of PDC analysis with other methods for water content determination in the solid insulation of new transformers [16].

Oil exchange mainly results in a significant reduction of initial polarization current values, fig. 6a,b. This is due to the better quality of the new oil. PDC-analysis of water content rM in the barriers was made by curve fitting and interpolation. Results were taken from the long term values. It can be seen that there is no significant reduction of water content. This is due to the hygroscopic properties of the barriers which means that most of the water is bond in the barriers and only a small amount is in the oil. Oil exchange removes a relatively small amount of water only.

Other diagnostic quantities can be calculated from PDC measurements being regarded as step responses, if field strength are low and stay in a linear range. Calculated $\tan \delta$ values below 10^{-2} Hz confirm that oil exchange does not reduce the water content in the barriers. Calculated values at 0.1 Hz are equal to directly measured values. Different values before and after oil exchange (0.9 and 0.19 resp.) are due to oil quality improvement. RVM "polarization spectra" were calculated from PDC measurements. They were identical with directly measured values. Significant differences of so called dominant time constants before and after oil exchange (5 s and 50 s resp.) were observed, but they are due to oil quality improvement and not to a reduction of water content in the barriers. This has to be stressed here in order to avoid misinterpretation of dielectric quantities.

Drying of the transformer by application of vacuum to circulating oil combined with low frequency heating LFH technology [13] shows a significant reduction of water content being in accordance with the extracted amount of water, fig. 6c, d.

6. FURTHER OPTIONS

Evaluation of water content in solid transformer insulation components is not the only possible application. There are some further options:

Grounded Equipment

Grounded test objects such as generator or cable insulations and insulation components adjacent to transformer core or tank can be measured by means of a potential free voltage source [17].

Ageing processes

PDC measurements also contain information about ageing processes. E.g. bushings in different stages of ageing could clearly be distinguished, fig. 7. The results corresponded to the results of further investigations.

In this case the bushings were not mounted on a transformer during the measurements. Normally it will not be practicable to dismount the bushings from the transformer just for measurements. Therefore selective measurements of insulations in mounted bushings will be valuable.

Selective Measurements

Generally selective measurements on parts of the insulation require three electrodes: Two electrodes form the boundaries of the insulation parts to be measured. All other electrodes are grounded and form a third electrode (like a guard ring electrode) collecting all the leakage currents not to be measured, fig. 4 (right). This kind of selective measurements is possible with PDC analysis and FDS only. Recovery voltages always are generated in a two electrode system between measuring electrode and ground. Therefore they are an integral answer of the whole insulation system only, including its surfaces.

Mounted Bushings

Selective dielectric measurements on mounted transformer bushings can be performed by application of the diagnostic voltage to the HV conductor and by taking the current response from the measuring tap which is connected to the outermost grading foil. It is reported that the signals are influenced by the environment of the bushing and it is assumed that leakage currents on the bushing surfaces [19] or within the transformer oil are not always negligible.

In a frequency domain description these leakage currents cause an additional phase angle shift between voltage and measured current. Therefore the measured (i.e. apparent) loss factor contains an unknown systematic error. In some cases even negative loss factors can be "measured", which

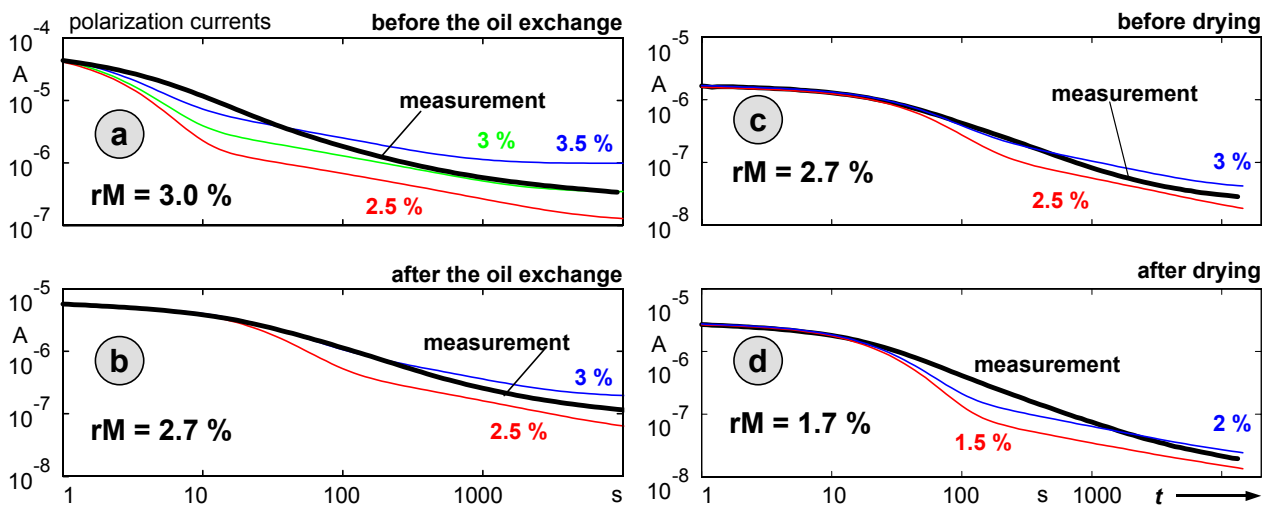


Fig. 6: Polarization current measurements on a 300 MVA power transformer before and after oil exchange (a and b) and drying (c and d). Moisture content rM is determined by curve fitting.

does not make any physical sense [20].

In a time domain description leakage currents, e.g. currents from the inner grading foils of the bushing to ground, also can influence polarization currents, fig. 8. But it is an advantage of time domain measurements that these influences can directly be described as superposition of time dependent currents. A clear understanding is easier without any further transformation. Investigations are under way to identify and quantify the influence of different environmental parameters in order to extract information about the bushing insulation itself.

7. CONCLUSIONS

Reliable information about the condition of transformer insulation can be extracted from PDC measurements by PDC analysis. It is a non-destructive method providing the moisture content in the solid insulation material and the conductivity of the oil. Other diagnostic quantities like $\tan \delta$, polarization index and polarization spectra can be calculated from PDC measurements directly.

Investigations of numerous transformers in new and aged status, of different designs, voltage levels and ratings show a good correlation between PDC results, results of Karl-Fischer titration and dew point measurements.

PDC diagnosis has the option to detect different stages of ageing and to measure different parts

Fig. 7:
PDC measurements on 400 kV OIP bushings in different stages of ageing.

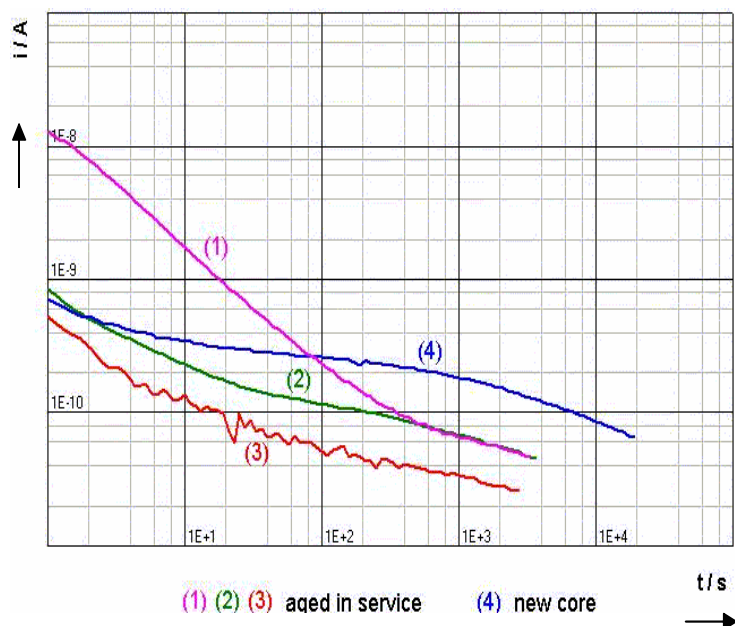
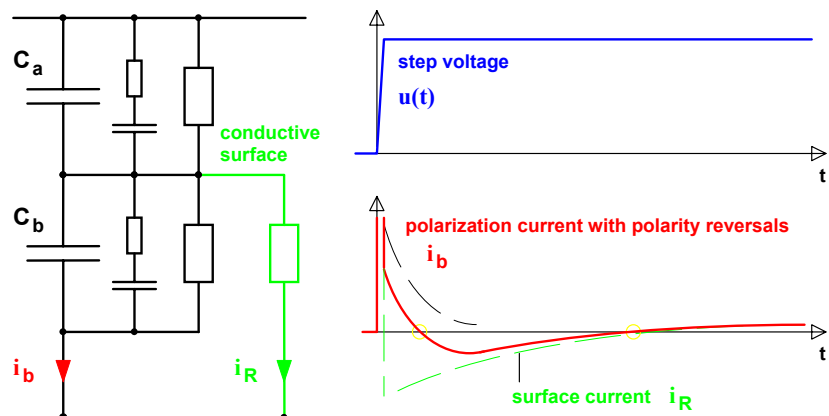


Fig. 8:
Influence of leakage currents on dielectric measurements (schematic).



of the insulation selectively (e.g. between windings, adjacent to ground, bushings).

Therefore, it may be concluded that the PDC analysis provides a valuable tool to assess the status of power transformer insulation and it seems to be applicable to other kinds of insulation systems.

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Authors:

⁽¹⁾ Corresponding author

Prof. Dr.-Ing. Andreas Kuechler⁽¹⁾
FH Würzburg-Schweinfurt
Ignaz-Schön-Str. 11
97421 Schweinfurt
Germany
+49 9721 940-840 Tel.
akuechler@fh-sw.de

Prof. Dr.-Ing. Thomas Leibfried
University of Karlsruhe
Kaiserstr. 12
76128 Karlsruhe
Germany
+49 721 608-2513 Tel.
leibfried@ieh.uni-karlsruhe.de

Ing. (grad) Bernd Breitenbach
E.ON Netz GmbH
Bernecker Str. 70
95448 Bayreuth
Germany
+49 921 915-4636 Tel.
bernd.breitenbach@eon-energie.com

Dr.-Ing. Jean Jaques Alf
ALFF Engineering
Gomweg 7, 8915 Hausen am Albis
Switzerland
+41 1 7766776 Tel.
alf@swissonline.ch

Dr.-Ing. Vahe Der Houhanessian
ALFF Engineering
Gomweg 7, 8915 Hausen am Albis
Switzerland
+41 1 7766776 Tel.
vahedh@swissonline.ch

Prof. em. Dr.-Ing. Walter S. Zaengl
Eichstockstr. 11
8600 Dübendorf
Switzerland
+41 1 8214310 Tel.
zaengl@swissonline.ch